The impact of an intense summer cyclone on 2012 Arctic sea ice retreat

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[1] This model study examines the impact of an intense early August cyclone on the 2012 record low Arctic sea ice extent. The cyclone passed when Arctic sea ice was thin and the simulated Arctic ice volume had already declined ~40% from the 2007–2011 mean. The thin sea ice pack and the presence of ocean heat in the near surface temperature maximum layer created conditions that made the ice particularly vulnerable to storms. During the storm, ice volume decreased about twice as fast as usual, owing largely to a quadrupling in bottom melt caused by increased upward ocean heat transport. This increased ocean heat flux was due to enhanced mixing in the oceanic boundary layer, driven by strong winds and rapid ice movement. A comparison with a sensitivity simulation driven by reduced wind speeds during the cyclone indicates that cyclone-enhanced bottom melt strongly reduces ice extent for about 2 weeks, with a declining effect afterward. The simulated Arctic sea ice extent minimum in 2012 is reduced by the cyclone but only by 0.15 \times 10^6 \text{km}^2 (4.4\%). Thus, without the storm, 2012 would still have produced a record minimum. Citation: Zhang J., R. Lindsay, A. Schweiger, and M. Steele (2013), The impact of an intense summer cyclone on 2012 Arctic sea ice retreat, Geophys. Res. Lett., 40, doi:10.1002/grl.50190.

1. Introduction

[2] On 26 August 2012, Arctic sea ice extent broke the previous record low of 4.17 \times 10^6 \text{km}^2 set on 18 September 2007, according to the National Snow and Ice Data Center (NSIDC) based on satellite observations. More remarkably, the record was broken in the middle of the melting season, more than half a month ahead of the usual time when the Arctic sea ice extent reaches a minimum. By 16 September, the NSIDC reported that the Arctic sea ice extent had dropped to its minimum for the year of 3.41 \times 10^6 \text{km}^2, a new record low, 18\% below the previous record minimum in 2007.

[3] The Arctic sea ice cover has been subject to years of shrinking and thinning in a warming environment [e.g., Meier et al., 2007; Comiso, 2012; Kwok and Rothrock, 2009] with a significant reduction in Arctic sea ice volume [Kwok et al., 2009; Schweiger et al., 2011]. The 26 August 2012 record followed the passage on 6–8 August of a large cyclone over most of the ice-covered areas of the Pacific sector (ICAPS) of the Arctic Ocean. Here ICAPS is defined as the satellite-observed ice-covered area before the cyclone on 4 August in the Pacific sector within 90–270°E, with a fixed area of 3.87 \times 10^6 \text{km}^2. The storm was unprecedented in extent, intensity, and depth [Simmonds and Rudeva, 2012]. According to the NCEP/NCAR daily reanalysis sea level pressure (SLP), the center of the low-pressure system was well within the sea ice pack, with a minimum central pressure of 974.5 hPa on 7 August (Figures 1a–1d). Simmonds and Rudeva [2012] report a lower minimum central pressure of 966 hPa on 6 August based on the higher resolution Climate Forecast System 6-hourly reanalysis. During the cyclone’s passage, surface winds exceeded 14 m s^{-1} in some locations, which is within the 99th percentile for August winds in the Pacific sector (Figures 1b, 1c, and 2a). Given the intensity of the cyclone, we ask: What was the impact of the storm on the ice, and did it have a significant role in creating the new record low Arctic sea ice extent? The coupled Pan-arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) [Zhang and Rothrock, 2003] is used to address these questions.

2. Model Description

[4] PIOMAS consists of a 12-category thickness and enthalpy distribution sea ice model [Zhang and Rothrock, 2003; Hibler, 1980] coupled with the POP (Parallel Ocean Program) ocean model [Smith et al., 1992]. The POP ocean model uses the nonlocal K-profile parameterization (KPP) scheme [Large et al., 1994] to determine vertical mixing and diffusion in the oceanic boundary layer. The model has 30 vertical ocean levels of varying thicknesses. There are six 5 m thick ocean levels in the upper 30 m and 13 levels in the upper 100 m, which is found to adequately resolve the near-surface temperature maximum (NSTM) layer in the Canada Basin [Steele et al., 2011]. The model is driven by daily NCEP/NCAR reanalysis atmospheric forcing including 10 m surface winds, 2 m surface air temperature (SAT), and downwelling longwave radiation and cloud fraction. SAT and cloud fraction are used to calculate downwelling shortwave radiation following Parkinson and Washington [1979].

[5] PIOMAS is first integrated from 1 January 1979 to 31 July 2012. This integration assimilates satellite observations of sea ice concentration and sea surface temperature data [Schweiger et al., 2011]. The data assimilation provides improved initial sea ice and ocean conditions for a continued integration over the focus period August–September 2012 that includes the cyclone’s passage. To create a physically consistent control simulation (CNTL), no assimilation is conducted after 1 August 2012. A sensitivity run (denoted ‘SEN’ hereinafter) is also conducted to assess the effect of the cyclone on the sea ice cover. SEN differs from CNTL only by 50% reduced magnitude of the surface winds during 5–9 August, thus largely removing the effect of the cyclone.
3. Results

In response to the storm, the model simulates a strong increase in ice speed in most of the ICAPS (Figures 1e–1h), where surface winds were intensified substantially (Figures 1a–1d). Inside the eye of the storm, ice motion is weaker. The strong increase in ice motion away from the eye may be attributed also to the thin (<1 m thick) ice cover in most of the ICAPS (Figure 1i). In fact, the simulated total ice volume during 1–12 August is lower than the past several years and ~40% lower than the 2007–2011 mean (Figure 2b). A thinner ice cover is weaker in mechanical strength and more susceptible to changes in wind forcing [Zhang et al., 2012]. Thus, the thin ice cover is preconditioned for a strong dynamic response to the cyclone as well as for a potentially rapid reduction in sea ice extent.

The cyclone occurred at a time of steady decrease in ice volume. However, the rate of decrease during 6–8 August 2012 is greater than before or after the storm and greater than the 2007–2011 mean on the same dates (Figure 2b). The simulated ice volume is $4.96 \times 10^3$ km$^3$ on 5 August and $4.32 \times 10^3$ km$^3$ 3 days later, a decrease of $0.64 \times 10^3$ km$^3$ or 12.9%. The 2007–2011 mean ice volume is $8.12 \times 10^3$ km$^3$ on 5 August and $7.83 \times 10^3$ km$^3$ 3 days later, a decrease of $0.29 \times 10^3$ km$^3$ or 3.6%. The 3 day (6–8 August 2012) volume loss of 12.9% is unprecedented. To assess this, we examine the in the wind forcing. Results are reported mainly from CNTL, unless stated otherwise.

Figure 1.  NCEP/NCAR reanalysis surface wind speed (a–d) and model-simulated sea ice speed (e–h), ice thickness on August 4 (i), thickness difference between 6, 7, and 10 August and 4 August (j–l), vertical diffusivity (VD) in the upper 15 m of the ocean (m–n), and ocean heat content change from 1 to 4 August (o) and from 5 to 8 August (p) in the 5–15 m depths (in m of ice equivalent). The white lines are NCEP/NCAR reanalysis SLP contours with contour interval of 10 hPa, and the black line represents satellite-observed ice edge defined by 0.15 ice concentration value (satellite ice concentration data are from http://nsidc.org/data/nsidc-0081.html). SLP and ice edge on 1 and 7 August are plotted on Figures 1o and 1p, respectively. The Canada Basin is marked by C in Figure 1a.
distribution of all 3 day volume losses that occurred during July and August over the period 1979–2011 (Figure 2i). We find that the 3 day storm-related volume loss, normalized by initial volume to account for a declining volume trend, is 1.7 times greater than any prior 3 day loss during July and August of 1979–2011 and 4.5 times greater than the 1979–2011 mean 3 day loss during July and August. Even without normalizing by volume, the 3 day storm-related volume loss of 0.64 $10^3$ km$^3$ is in the 75th percentile. The rapid reduction in ice volume during the storm is due to enhanced ice melt (Figures 3a–3d). The simulated total ice melt is 0.12 $10^3$ km$^3$ d$^{-1}$ before the cyclone, but almost doubled during the cyclone, averaging $0.21 \times 10^3$ km$^3$ d$^{-1}$ (or $0.17 \times 10^3$ km$^3$ d$^{-1}$ in the ICAPS) during 6–8 August (Figure 2c and Table 1). The enhanced melt is widespread in the ICAPS, but is strongest in the Canada Basin, where ice melt is as high as 0.12 m d$^{-1}$ (Figures 3b and 3c). This explains the large decrease in ice thickness during the storm in these areas (Figures 1j–1l), up to 0.5 m by 10 August (Figure 1l). The simulated ice in most of these areas was already thin on 4 August before the storm (Figures 1i and 2b). It is no surprise that, because of the elevated ice melt, satellite observations showed a much-reduced ice extent there by 10 August (e.g., Figures 1h and 4a).

Figure 2. Simulated sea ice speed and NCEP/NCAR reanalysis surface wind speed averaged over the ICAPS (a), simulated 2007, 2011, 2012, and 2007–2011 mean ice volume (b), total melt, top melt, and bottom melt (c), and bottom melt due to ocean dynamic heat transport and due to atmospheric heating of the ocean SML (d) integrated over the Arctic Ocean, simulated surface NHF, net RHF, and THF averaged in the ICAPS (e), simulated ocean heat content and vertical diffusivity averaged in the upper 15 m of the ICAPS (f), simulated vertical profiles of upper ocean temperature (g) and vertical diffusivity (h) averaged over the ICAPS, and simulated distribution of 3 day ice volume losses during July–August and in several extreme wind events (defined by daily wind speeds in the ICAPS exceeding 14 m s$^{-1}$; color dots and black cross) over the period 1979–2012 (i) and distribution of 3 day ocean heat losses in the upper 15 m during July–August of 1979–2012 (j). In Figure 2i, dots in bluish colors show significant 3 day ice volume losses in extreme wind events that occurred mostly in recent years.
To understand what caused the increase in ice melt during the cyclone, melt components are calculated as follows:

\[ M_{\text{tot}} = M_{\text{top}} + M_{\text{bot}} \]

where \( M_{\text{tot}} \) is the total melt, \( M_{\text{top}} \) is top melt due to surface atmospheric heat (including radiative and turbulent heat fluxes), and \( M_{\text{bot}} \) is bottom melt due to ocean heat and defined here as the combined melt at the bottom and perimeter of ice floes. Bottom melt \( M_{\text{bot}} \) may be further partitioned as [Steele et al., 2010] follows:

\[ M_{\text{bot}} = M_{\text{botO}} + M_{\text{botA}} \]

where \( M_{\text{botO}} \) is the bottom melt due to ocean dynamic heat transport (i.e., via ocean advection, diffusion, and

Figure 3. Model-simulated total sea ice melt (in m d\(^{-1}\)) (a–d), top melt (e–h), bottom melt (i–l), bottom melt due to atmospheric heating of the ocean SML (\( M_{\text{topA}} \)) (m–p), and bottom melt due to ocean dynamic heat transport (\( M_{\text{botO}} \)) (q–t, reduced color range). The black line represents satellite-observed ice edge on the listed date, and the white line represents satellite-observed ice edge on 16 September 2012 with the minimum ice extent of the year.
conviction) and $M_{botA}$ is the bottom melt due to local atmospheric heating of the ocean surface mixed layer (SML) when surface heat flux (radiative or turbulent) enters the SML through leads or open water.

[12] The increase in the simulated total melt during the storm is not due to top melt, which is relatively small in magnitude and decreases slightly during the storm (Figures 2c and 3e–3h). The decrease in top melt is due to a decrease in the simulated surface net heat flux (NHF; turbulent plus radiative heat fluxes) (Figure 2e). The decrease in NHF is in turn due to a decrease in the net surface radiative heat flux (RHF, shortwave plus longwave), owing to the cloud cover that reduced the downwelling shortwave radiation (not shown). In contrast, the simulated surface turbulent heat flux (THF, sensible plus latent heat fluxes) increases (Figure 2e), owing to the strong winds that enhanced turbulent exchange at the surface. However, the decrease in RHF is greater than the increase in THF on 7 August and the following days, leading to the decrease in NHF.

[13] The increase in the total melt is due to a strong increase in bottom melt over most of the ICAPS throughout the cyclone (Figures 2c and 3i–3l and Table 1). One of two contributing heat sources for bottom melt, atmospheric heating of the ocean SML, $M_{botA}$, is not a significant contributor. $M_{botA}$ dominates before the cyclone, at about twice the magnitude of the bottom melt due to ocean dynamic heat transport, $M_{botO}$ (Figure 2d and Table 1). However, on average, over the whole storm period (6–8 August), there is no significant increase in the integrated $M_{botA}$ (Figures 2d and 3m–3p and Table 1) because of the reduction in RHF throughout the storm that leads to a reduction in NHF during 7–8 August (Figure 2e). Instead, the strong increase in bottom melt is due to ocean dynamics. The average bottom melt due to ocean dynamic heat transport $M_{botO}$ is amplified by a factor of 4, to about twice the magnitude of $M_{botA}$ during the cyclone (Figure 2d and Table 1). Increases in $M_{botO}$ are apparent over most of the ICAPS, except inside the eye of the cyclone (Figures 3q–3t). The strongest increases, more than 0.1 m d$^{-3}$, are in the Canada Basin.

[14] The increase in ocean dynamic heat transport during the cyclone is due to enhanced heat entrainment into the SML from the NSTM layer [Jackson et al., 2012]. The NSTM is at ~15 m depth on average before the cyclone (Figure 2g). During 1–4 August, the NSTM and hence the upper ocean heat content increase (Figures 1o and 2g), owing mainly to solar energy input. Significant heat loss occurs in the NSTM layer during the cyclone (Figure 2f), owing to enhanced entrainment into the SML where this heat is then available to melt ice. The total heat loss in the NSTM layer over the ICAPS during 6–8 August is found to be equivalent to the total 3 day bottom melt of 0.30 × 10$^3$ km$^3$ due to ocean dynamic heat transport (Table 1). Particularly large heat losses occur in the Canada Basin, equivalent to up to 0.4 m ice melt over the 3 day period in some locations (Figure 1p). The impact of this storm on ocean heat loss is also unprecedented; it exceeds any previous 3 day loss by a factor of 1.7 and any 1979–2011 mean 3 day loss during July–August by a factor of 7 (Figure 2j).

[15] The cyclone enhanced the vertical diffusivity in the upper 15 m of the ICAPS (Figure 2f). Depending on the vertical turbulent fluxes of momentum, vertical diffusivity is calculated based on the KPP parameterization of oceanic boundary layer mixing [Large et al., 1994]. Strong winds and rapid ice movement tend to amplify the vertical momentum transfer, which leads to stronger vertical mixing and larger diffusivity. This is why the increase in vertical diffusivity is closely aligned in time with the increase in wind and ice speed (Figures 2a and 2f). The increase in vertical diffusivity is also aligned with the decrease in the heat

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**Table 1. Three Day Mean Ice Melt (10$^3$ km$^3$ d$^{-1}$) Before (2–4 August 2012), During (6–8 August), and After (10–12 August) the Cyclone, Integrated over the Arctic Ocean and the ICAPS (in Parentheses)**

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>During</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total melt</td>
<td>0.12 (0.08)</td>
<td>0.21 (0.17)</td>
<td>0.08 (0.07)</td>
</tr>
<tr>
<td>Top melt</td>
<td>0.03 (0.02)</td>
<td>0.02 (0.02)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>Bottom melt</td>
<td>0.09 (0.06)</td>
<td>0.19 (0.15)</td>
<td>0.07 (0.06)</td>
</tr>
<tr>
<td>Bottom melt due to ocean dynamic heat transport</td>
<td>0.03 (0.02)</td>
<td>0.12 (0.10)</td>
<td>0.03 (0.03)</td>
</tr>
<tr>
<td>Bottom melt due to atmospheric heating of the SML</td>
<td>0.06 (0.06)</td>
<td>0.07 (0.06)</td>
<td>0.04 (0.04)</td>
</tr>
</tbody>
</table>

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**Figure 4.** Satellite-observed and model-simulated Arctic sea ice extent (a) and difference in ice extent between the SEN and CNTL runs (b) over 1 August to 25 September 2012. The dates marked with vertical lines show when the 2007 ice extent minimum record was first broken and the time of the minimum extent in 2012.
content of the NSTM layer. Vertical diffusivity increases over most of the ICAPS (Figures 1m and 1n); the areas of increasing diffusivity follow the SLP contours in areas of strong winds (Figures 1b and 1c). The vertical diffusivity profiles averaged over the ICAPS show a substantial increase during the storm (Figure 2h), mainly in the upper 15 m where the NSTM provides a heat source (Figure 2g).

[16] In an effort to quantify the role of the cyclone-enhanced bottom melt in the new record low Arctic sea ice extent, we compare the simulated ice extent from the model run with and without the wind forcing of the cyclone (Figure 4). CNTL tends to underestimate ice extent in early August and overestimate it in September when compared to satellite observations (Figure 4a). However, the model bias of the minimum ice extent on 16 September is small at 0.06 × 10^6 km^2, or 1.8%. Without the cyclone forcing, SEN does not generate strong bottom melt (not shown). As a result, the SEN-simulated ice extent is greater than the CNTL simulated during and after the storm (Figure 4b). The difference in ice extent between SEN and CNTL increases to a maximum of 0.48 × 10^6 km^2 on 21 August, indicating that the impact of the cyclone-enhanced bottom melt on ice extent remains strong over at least a half month. After 21 August, the difference decreases and the effect of the cyclone fades. By 16 September, the difference is reduced to 0.15 × 10^6 km^2, which is small compared to, for example, the difference between the 2007 and 2012 sea ice extent minima of 0.76 × 10^6 km^2. Thus, even without the August cyclone, a new record minimum ice extent in 2012 would have occurred. However, the storm did contribute to the magnitude of this record and affected the timing; i.e., simulations indicate that the storm forced the 2012 ice extent to dip below the 2007 record minimum 10 days earlier than would have occurred in its absence (Figure 4b).

4. Concluding Remarks

[17] Model results indicate that the early August 2012 cyclone did affect the September minimum Arctic sea ice extent but only by a relatively small amount. Nonetheless, the simulated impact of the cyclone on sea ice is strong during and in the immediate aftermath of the cyclone. When the cyclone reached the ICAPS during 6–8 August, ice melt was enhanced and ice thickness decreased rapidly in much of the Canada Basin. The enhanced ice melt is attributed mainly to an increase in bottom melt due to stronger upward ocean heat transport. The increase in upward heat transport is caused by enhanced heat entrainment from the NSTM layer to the SML, driven by strong winds and ice motion, such that the heat content in the NSTM layer is reduced during the storm.

[18] Although the cyclone lasted only a few days, the strong impact of enhanced bottom melt on ice extent persists for more than a half month. Ice extent was reduced by much as 0.48 × 10^6 km^2 in the aftermath of the cyclone. Beyond a half month, the effect of the cyclone subsides. Without the storm, the modeled minimum Arctic ice extent in 2012 is 3.56 × 10^6 km^2, still a new record low. However, our quantification of the cyclone’s impact using PIOMAS may be biased low because PIOMAS does not include an atmospheric model component and thus is unable to capture the changes in air-sea and ice-sea interactions after the storm. On the other hand, the lack of an interactive atmosphere is less critical from mid-August to mid-September when air temperatures are not strongly affected by the presence of sea ice.

[19] Stronger winds during the cyclone not only increase ice motion and hence deformation, but also generate waves and wave-induced ice fragmentation. These processes are currently not simulated in PIOMAS. However, even with stronger ice deformation and wave-induced fragmentation, their impact via the ice-albedo feedback is less important during the storm because of decreasing RHF over most of the ICAPS. The fact that solar radiation levels are already low during the cyclone passage in early August diminishes the likely impact of these processes.

[20] There are some key differences between the conditions leading to the new record set in 2012 and those leading to the previous record set in 2007. In summer 2012, the simulated ice cover is much thinner (Figure 2b) and thus more vulnerable to changes in atmospheric and oceanic forcing and easier to shrink. The cyclone was intense enough to cause stronger upward heat transport in a normally well-stratified summer ocean, leading to enhanced bottom ice melt. Because of the short duration of the storm, ice mass advection is not a significant factor; cyclone-enhanced ice motion only advances ice by additional 9 km d⁻¹ on average. In the summer of 2007, sustained southerly wind anomalies drove ice away from much of the Pacific sector toward Fram Strait during much of the melting season from July to September, leaving behind a large area of open water and thin ice where ice-albedo feedback caused amplified ice melt [Zhang et al., 2008; Lindsay et al., 2009].

[21] The impact of cyclones on Arctic sea ice is likely to grow if the ice cover continues to thin, given that the largest storm-associated ice volume losses occurred in the most recent years (Figure 2i). Summer ice extent will continue to fluctuate from year to year because of natural variability. However, because of the thin ice cover, any year in the future has the potential to set a new record in low ice extent. Strong summer cyclones or persistent wind anomalies are likely to affect the timing and magnitude of any future record.

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References